ACCRETION PROCESSES AROUND BLACK HOLES AND NEUTRON STARS: ADVECTIVE DISK PARADIGM

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Abstract. We review models which include advective accretion disks onto compact objects and discuss the influence of the centrifugal pressure supported high density region close to the compact objects on the emitted spectra. We show that the stationary and non-stationary spectral properties (such as low and high states, quasi-periodic oscillations, quiescent and rising phases of X-ray novae, etc.) of black hole candidates could be satisfactorily explained by the advective disk models.

1. Introduction

Physics of accretion has undergone major revisions in every twenty years or so. In the 1950s, spherical accretion onto compact stars was studied rather extensively. This so-called Bondi flow (Bondi 1952) is radiatively very inefficient as matter has a very high radial velocity and therefore, for a given accretion rate, it has a very low density. When quasars and active galactic nuclei (AGN) were discovered, it was impossible to explain their luminosity by using the properties of the Bondi flow, and several workers engaged in finding ways to increase the efficiency of the flow by addition of magnetic field and plasma processes (see, Chakrabarti 1996a [C96a] for a recent review). Partially to resolve the efficiency problem, and partially otherwise, in the 1970s, another extreme form of accretion, namely, the Keplerian disk models, became popular thanks to the pioneering works of Shakura & Sunyaev (1973, [SS73]) and Novikov & Thorne (1973). Here the disk is always assumed to have the Keplerian angular momentum distribution and the flow pressure and advection effects were assumed to be negligible. The energy generated locally by viscous dissipation is assumed to be totally radiated away. Although the inner edge of the disk is assumed to coincide with the innermost stable circular orbit and no attempt was made to satisfy inner boundary condition on the horizon, this disk model nevertheless, was *very* successful in explaining the 'big blue bump' observed in the active galaxies as well as the soft X-ray bump observed in low mass binary systems. However, the galactic black hole candidates were soon found to appear in roughly two distinct states, one is the soft state and the other is the hard state (see, Ebisawa, Titarchuk & Chakrabarti, 1996 [ETC96] for a list of known candidates and their

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observed states). In soft states, more power is emitted in soft X-rays and the multicolor-black body bump comes along with a weak power law component of slope $\alpha \sim 1.5$ ($F(\nu) \sim \nu^{-\alpha}$). In hard states, on the contrary, more power is emitted in hard X-rays; soft bump is faint or nonexistent, and the power law component has a slope of $\alpha \sim 0.5$. Such observations clearly challenged the simplistic Keplerian disk model and a further revision of the disk model was necessary.

2. Accretion Flows of 1990s: The Advective Disks

Not surprisingly, theoreticians sensed the inadequacies of the standard Keplerian disk models in early 1980s. Paczyński & Bisnovatyi-Kogan (1980) wrote down the so-called advective disk equations which contained the advection and pressure terms. For optically thick disks, solutions were being tried out under various assumptions. In slim disk model (Abramowicz et al., 1988) it was shown that (locally) the disk no longer has the viscous and thermal instability when advection was added, but the global solution was found to be incorrect as the angular momentum was seen to deviate from a Keplerian distribution far away from the black hole. First completely global solutions of the viscous, advective disks were presented in Chakrabarti (1990a, [C90a]) where it was assumed that the heating and cooling were so adjusted that the flow would be isothermal. These assumptions were removed afterwards (Chakrabarti 1996b, [C96b]) and the conclusions about the topology of the solutions remained the same. Both optically thin and optically thick single temperature solutions were obtained. Generally speaking, the fundamental points in an advective disk is the following:

Matter entering a black hole must possess radial velocity comparable to the velocity of light on the horizon and as a result the flow must be super-sonic and sub-Keplerian (Chakrabarti 1990b [C90b]; C96ab). The advective flow deviates from a Keplerian disk away from the black hole depending on viscosity and cooling/heating processes and eventually passes through a sonic point before entering the hole. If the flow is hot enough (or, away from equatorial plane), it may also pass through a standing shock and subsequently, through a second (inner) sonic point. On a neutron star, on the other hand, the flow may remain subsonic throughout, or, if it ever becomes super-sonic, it must pass through a shock at the outer edge of the boundary layer. This is because the radial flow must stop due to pressure of the radiation emitted from the surface and hence the flow must be sub-sonic. A thin boundary layer is produced within which both the rotational velocity and radial velocity reach the star-surface values.

The formation of a centrifugal pressure supported standing shock around a black hole comes about because of the following reason: close to the black hole, the infall time scale of the flow is usually very small compared to the time scale of viscous transport of angular momentum. As a result, angular momentum remains almost constant in last tens of Schwarzschild radii (if the viscosity is small enough) and the centrifugal force increases faster compared to the gravitational force. Matter piles up behind the centrifugal barrier and a shock forms. The shock need not be sharp, i.e., the jump in temperature and density may be gradual, depending on the viscosity of the flow. The important

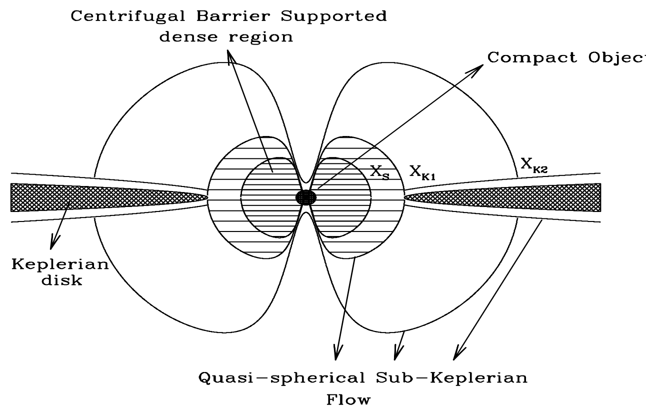

Fig. 1: Schematic diagram of the multi-component advective disk model. Keplerian disk component which eventually becomes sub-Keplerian close to a compact object is flanked by a sub-Keplerian halo component which originates from the Keplerian disk farther out (depending on viscosity) and possibly contributed by winds of the companion or nearby stars. Giant predominantly rotating disk of size $\sim 10^{3-4}x_g$ forms an extended atmosphere which reprocesses radiations emitted from inner disks.

point is that the flow slows down close to the hole and forms a dense ionized cloud of hot gas. Farther close to the hole, the flow passes through the inner sonic point and enters into the hole supersonically. When the viscosity is high, the centrifugal barrier is absent altogether and Keplerian disk would be present till close to the marginally stable orbit. This approach of the Keplerian disk towards the hole is gradual as the extent of viscosity (and therefore accretion rate of the Keplerian component) is increased. This phenomena is a part of solutions of the viscous transonic flow (C96b) and has been confirmed by XTE observations rather adequately (Zhang et al., 1997).

Given the above description of the solution (which will be quantified below), one can imagine that the most general nature of accretion disk that could form around a black hole would consist of several components as shown in Fig. 1. This picture is also valid in wind fed binary systems as well as in active galactic nuclei where the stellar winds are also accreted. The inherent assumption that is involved in such a picture is that the viscosity parameter (SS73) is decreasing away from the equatorial plane and that the angular momentum and the inner sonic point close to the black hole are roughly similar at all heights. High viscosity advective flows near the equatorial plane continue to form a Keplerian disk all the way close to the black hole, but the low viscosity (with alpha parameter ~ 0.05) flows deviate from a Keplerian disk and has the centrifugal pressure supported dense region close to the black hole. Flow with even smaller viscosity $\alpha \lesssim 0.001$) may form a gigantic extended atmosphere which is basically rotating as an ion torus of size $\sim 10^{3-4}x_g$, where $x_g = 2GM/c^2$ is the Schwarzschild radius of the central black hole of mass M.

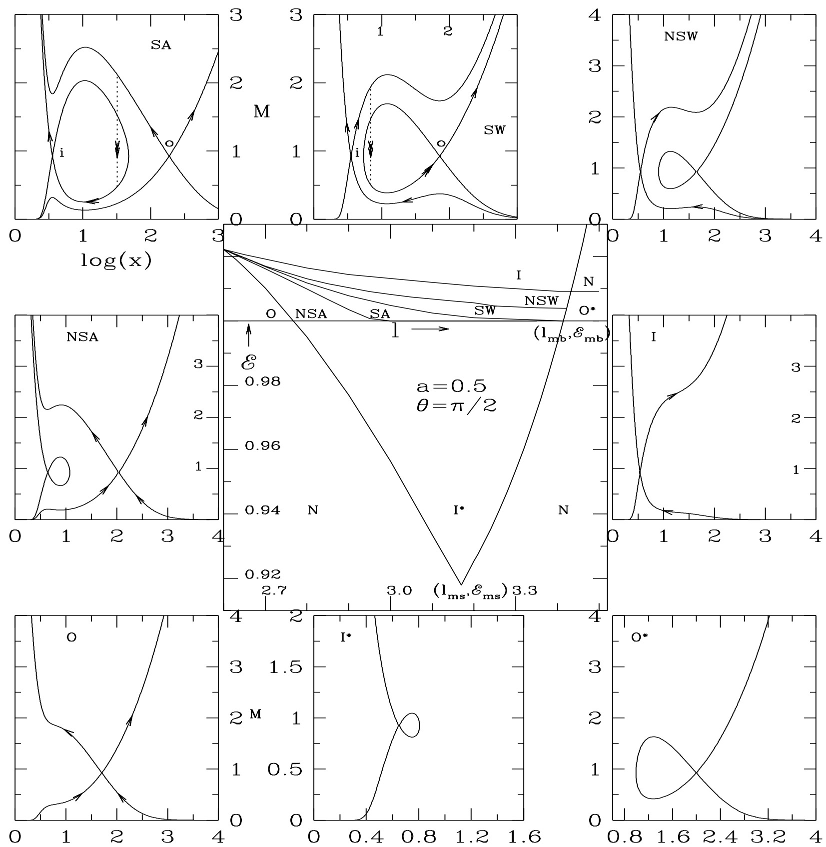

Fig. 2: Classification of the *entire* parameter space (central box) in the energy-angular momentum plane in terms of topological variation of the Kerr black hole accretion ($a = 0.5$ and polytropic index $\gamma = 4/3$). Eight surrounding boxes show the solutions from each independent region of the parameter space. Contours are of constant entropy accretion rate $\dot{\mathcal{M}}$. Arrowed curves are the solutions which pass through sonic points. Vertical arrowed lines correspond to shock transitions.

Fig. 2 shows the classification of the *entire* parameter space according to the types of solutions of inviscid flows around a black hole (Chakrabarti 1996c [C96c]; see also Chakrabarti 1989 [C89]; C90b). In the central box, the parameter space (spanned by specific angular momentum l and specific energy $\mathcal{E}$) is divided into nine regions marked by N, O, NSA, SA, SW, NSW, I, O^*, I^*. The horizontal line at $\mathcal{E} = 1$ corresponds to the rest mass of the flow. Surrounding this parameter space, various solutions (Mach number $M = v_x/a_s$ vs. logarithmic radial distance x where v_x is the radial velocity and a_s is the sound speed) marked with the same notations (except N) are plotted. The accretion solutions have inward pointing arrows and the wind solutions have outward pointing arrows. The region N has no transonic solution. E and l are the only two parameters required to describe the entire inviscid global solutions. Since E is assumed to be constant, entire energy is advected towards the hole. Thus, these solutions are hot but inefficient radiators very similar to their spherical counterpart (Bondi flow). The constancy of energy is roughly guaranteed in optically thin solutions only. Modifications of these solutions in

viscous flows which include heating and cooling are in C96b. In the case of neutron star accretion, the subsonic inner boundary condition forces the flow to choose the sub-sonic branch and therefore the energy must be dissipated at the shock (at x_{s1} or x_{s3} in the notation of C89) outside the neutron star surface (C89; C90b; C96b) unless the entire flow is subsonic. This is the essential difference between black hole and neutron star accretions: In the black hole accretion the total luminosity could be much less compared to the maximum luminosity permitted by general relativistic considerations (C96a) since the rest could be advected through the horizon (as we see here, perfectly stable solutions exist even with constant specific energy), while in neutron stars (at least when the magnetic field is absent) the matter must emit all radiations outside the star surface. The solutions from the region 'O' has only the outer sonic point. The solutions from the regions NSA and SA have two 'X' type sonic points with the entropy density S_o at the outer sonic point *less* than the entropy density S_i at the inner sonic point. However, flows from SA pass through a standing shock since the Rankine-Hugoniot conditions are satisfied. The entropy generated at the shock $S_i - S_o$ is advected towards the black hole to enable the flow to pass through the inner sonic point. These advective disk solutions have been verified to be *stable* by detailed numerical simulations (Chakrabarti & Molteni, 1993; Molteni, Lanzafame & Chakrabarti, 1994; Molteni, Ryu & Chakrabarti, 1996). Rankine-Hugoniot conditions are not satisfied for flows from the region NSA. Numerical simulations show (Ryu, Chakrabarti & Molteni, 1997 [RCM97]) that flows from this region are very unstable and exhibit periodic changes in emission properties as they constantly try to form stationary shocks, but fail to do so. The frequency and amplitude of modulation (10-50%) of emitted X-rays have properties similar to Quasi-Periodic Oscillations (QPOs) observed in black hole candidates (Dotani, 1992). In galactic black holes, these frequencies are around 1Hz (exact number depends on shock location, i.e., l, $\mathcal{E}$ parameters) but for extragalactic systems the time scale could range from a few hours to a few days depending on the central mass ($T_{QPO} \propto M_{BH}$). Numerous cases of QPOs are reported in the literature (e.g., Dotani, 1992; Halpern & Marshall, 1996; Papadakis & Lawrence, 1995). In presence of cooling effects, otherwise stationary shocks from SA also oscillate with frequency and amplitude modulations comparable to those of QPOs *provided* the cooling timescale is roughly comparable to the infall timescale in the post-shock region (Molteni, Sponholz & Chakrabarti, 1996, [MSC96]). Kilohertz oscillations on neutron stars are also possible when the shock at x_{s1} form (typically, at $2.5x_g$, just outside the neutron star surface). This is because the Comptonization time scale and the infall time scale are both comparable to $\sim 0.001s$ (Chakrabarti & Titarchuk, in preparation). The solutions from the regions SW and NSW are very similar to those from SA and NSA. However, $S_o \geq S_i$ in these cases. Shocks can form only in winds from the region SW. Shock conditions are not satisfied in winds from the region NSW. This makes the NSW flows unstable as well. A flow from region I has only the inner sonic point and thus can form shocks (which require the presence of two saddle type sonic points) if the inflow is already supersonic due to some other physical processes (as in a wind-fed system). Each solution from regions I^* and O^* has two sonic points (one 'X' and one 'O') only and neither produces complete and global solution. The region I^* has an inner sonic point but the solution does not extend subsonically to a large distance. The region O^*

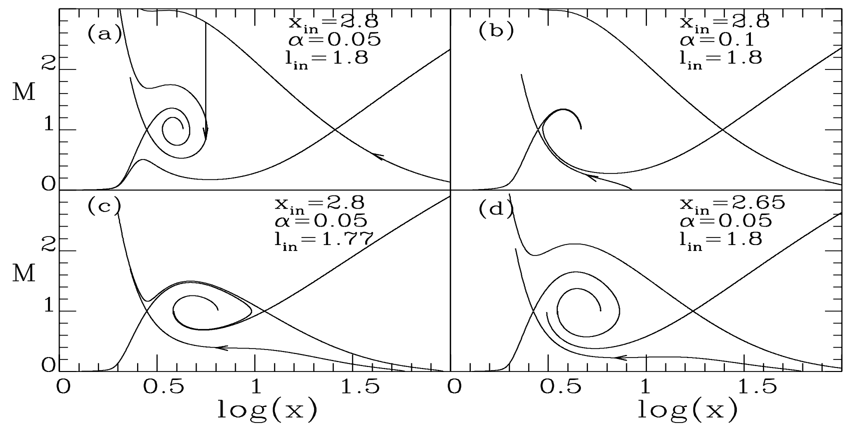

Fig. 3: Change in solution topology of a viscous flow as all three parameters are varied (C90a). In (a), after deviating from a hot Keplerian disk the flow can pass through the outer sonic point, shock and the inner sonic point (shown in arrows), while in (b-d) the stable flow can pass through the inner sonic point after it deviates from a Keplerian disk. Density and velocity distributions in the flow close to the black hole remain roughly the same in all these cases. Distance x is measured in units of x_g.

has an outer sonic point, but the solution does not extend supersonically to the horizon! When a significant viscosity is added, the closed topology of I^* opens up and then the flow joins with a cool Keplerian disk (C90ab; C96b) which has $\mathcal{E} < 1$. These special solutions of viscous transonic flows should not have shock waves. However, hot flows deviating from a Keplerian disk or sub-Keplerian companion winds, or flows away from an equatorial plane (C96d) or, cool flows subsequently preheated by magnetic flares or irradiation can have $\mathcal{E} > 1$ and therefore standing shock waves. Note that in order to have standing shocks, one does not require large angular momentum. In majority of the cases, the flow needs to have $l << l_{ms}$, the marginally stable value (Fig. 2). Although an adiabatic flow with polytropic index $\gamma < 1.5$ does not have shocks, the stationary observational properties, which depend only on the enhanced emission from the region behind of centrifugal barrier, are not affected.

When viscosity is added, the closed topologies shown in Fig. 2 open up as the 'O' type sonic points become spiral or nodal type. Singularly important in this context (perhaps the most important understanding in the accretion disk physics since Bondi flow!) is the non-trivial change in topology when each of the three free parameters are changed (C90ab). In the context of viscous isothermal flows (These discussions are valid for a general flow as well, see, C96ab.) these free parameters can be chosen to be inner sonic point x_{in} (this replaces the specific energy parameter), the angular momentum on the horizon l_{in} and the viscosity parameter α. Temperature of the disk is computed self-consistently from these parameters. Fig. 3 shows that transition to topology in (b-d) from topology (a) can take place either by increase in viscosity or decrease x_{in} or l_{in}. In (a), shocks are still possible, while in (b-d), shocks do not form as the flow enters into the hole through the inner sonic point straight away from a Keplerian disk, but the density variation and emission properties remain similar to that of

a shocked flow. In (b), Keplerian disk is extended close to the horizon, while in (a) the deviation takes place farther outside of the outer sonic point. Thus, for instance, if there is a vertical variation of viscosity in a Keplerian disk very far away from a black hole, it is possible that different layers would deviate from a Keplerian disk at different radial distance, and a sub-Keplerian flow (with or without a shock) would surround a Keplerian disk as the flow approaches the compact object as shown in Fig. 1. This two-component advective flow (TCAF) Model (Chakrabarti & Titarchuk, 1995 [CT95]), for the first time, does not require any ad hoc Compton cloud or magnetic coronae to explain the power law components of black hole spectra. Here, one computes the properties of the so called 'Compton cloud' self-consistently since it is a part of the inflow itself.

In C96b, it is shown that the variation of the flow velocity (and hence the flow density) close to the black hole is similar whether the shock forms or not (Fig. 7a of C96b). Hence, *qualitative* spectral properties of the TCAF Model does not seriously depend on whether the shocks actually form in either or both of the Keplerian (which also becomes sub-Keplerian close to the hole) and the sub-Keplerian components. However, spectral properties *do depend* upon whether the accretion flow is of single component (such as one Keplerian flow becoming entirely sub-Keplerian close to the hole) or two components (where the original Keplerian disk plus companion winds are segregated into Keplerian and sub-Keplerian components very far away before being mixed into a single sub-Keplerian component near the hole). This will be demonstrated below. In this context, it is to be remembered that the sub-Keplerian flow can really be made up of two distinct components (Fig. 1): one passes through the inner sonic point (forming the giant disk; the solutions in g11-g41 grids of Fig. 2a of C96b) and the other forms a shock (forming the centrifugally supported dense region, the solution in grid g12-g42 of Fig. 2a of C96b). The central Keplerian disk comes form the grid g13-g14 of the same Figure.

3. Observational Properties of Multi-Component Advective Flows.

Based upon above theoretical unstanding of the properties of advective flows, CT95 pointed out that the accretion on most compact objects may be taking place in two components: one is of higher viscosity, predominantly Keplerian (Disk Component) and is extended till around $x_K \sim 10x_g$ or less if the accretion rate is high enough to keep it thermally and viscously stable, otherwise x_K could be higher (see also, ETC96). Keplerian region of the disk component supplies soft photons. The other component (Halo Component) is predominantly sub-Keplerian (which is originated from the Keplerian disk far away and is contributed by companion winds, if present, in the case of a galactic black hole and by winds from numerous stars in the case of a supermassive black hole.). This component radiates inefficiently and therefore is hot ($\sim$ virial temperature; see Rees, 1984) and together with $x < x_K$ of the disk component they supply hot electrons which in turn energize intercepted soft photons (determined by the disk component) to produce the hard component. The extent to which electrons cool is determined by the accretion rates in these two components. At least three important variations of this Model is recognized (Chakrabarti, 1997 [C97]): TCAFM1– In this case, the halo component forms a strong shock be-

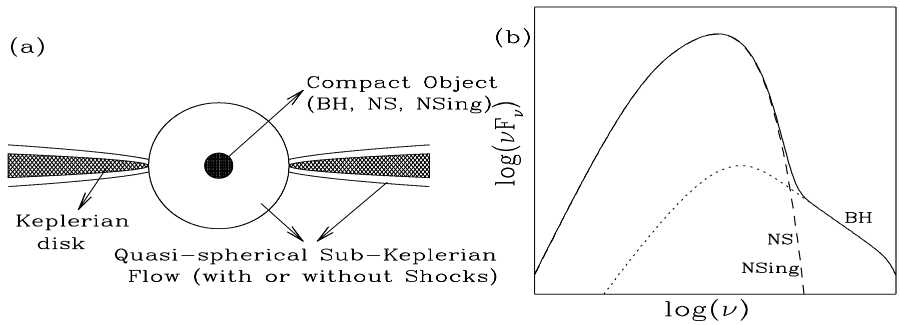

Fig. 4: (a) The idealization of Advective flow model of Fig. 1 and (b) its spectra in soft states. Soft states of neutron stars (NS), black holes (BH) and naked singularities (NSing) are distinguished by the presence or absence of the weak hard tail component due to bulk motion Comptonization (CT95).

hind the centrifugal barrier: $x_s \sim 10x_g$ and puffs up and mixes up with the disk component at $x < x_s$. TCAFM2– The halo component does not form a shock or forms only a weak shock but still feels the centrifugal barrier as in TCAFM1. The results in these two models are similar. TCAFM3– The halo component is completely devoid of angular momentum. The disk component deviates from a Keplerian disk at x_K. For $x < x_K$ these components mix as before. In this case, the absence of centrifugal barrier reduces the optical depth of the region $x < x_K$ and it is easy to cool this region even at a low disk rate. A corollary of these Models is a single component model SCAFM, where the sub-Keplerian component rate is so low that it is practically non-existent. In SCAFM, soft photons of the Keplerian region may or may not cool the hot electrons of its own sub-Keplerian region (for $x < x_K$) very effectively depending on x_K and the spectra remains soft in most of the parameter space. Also, in this case, the hard and soft components are always anticorrelated while observations suggest that very often they behave independently. In CT95, TCAFM1 is extensively studied while other possibilities are also mentioned (see also ETC96). More detailed study of these models are in C97. Note that the generalized disk (Fig. 1) of the 1990s (and hopefully of the future) is really a natural combination of purely advecting Bondi flow of the 1950s and purely rotating Keplerian disks of the 1970s. In Fig. 4 we show the basic difference in the soft state spectra of neutron stars and black holes. In the soft state, the disk rate is large and emitted soft photons completely cool the inner quasi-spherical sub-Keplerian region. The inner boundary property on the horizon of a black hole causes the cool (but rushing with velocity comparable to the velocity of light) electrons to Comptonize a fraction of these soft photons due to direct momentum transfer (as opposed to random momentum transfer in thermal Comptonization) and produces a weak hard tail component with photon index $\sim 2.5 - 3$. While on a neutron star such a hard component must be missing since the flow has to slow down on the inner boundary. Just for completeness, we wish to point out that a naked singularity (NSing, with inner boundary at $x \sim 0$) also should not

have this weak hard tail since extremely dense advecting matter close to the singularity would carry all such hard photons inwards. This feature is because the absorbing boundary is at $x = 0$ rather than at $x = 1.5$ (CT95; also see, Chakrabarti & Sahu, 1997). Note that due to thermal Comptonization when the soft state is produced at around $\dot{m}_d \sim 0.1 - 0.3$ the energy spectral index can also be around $1.5 - 2.0$, but the power law is not extended till several hundred keV as in bulk motion Comptonization. (Occasionally, this soft state without the extended power law is simply called the 'soft state' while that with an extended power law which is called 'very soft state'; see Grebenev et al, 1994.) Note also when relativistic corrections are added the cutoff by the bulk motion Comptonization occurs at $4m_e c^2/\dot{m}$ (Titarchuk, 1997) rather than at $m_e c^2/\dot{m}$ as in CT95. Thus the extended power law due to the bulk motion Comptonization could be as high as $\sim 1MeV$. Indeed all the observed black hole candidates have this extended power law. It is possible that the power law component may actually exist beyond $\sim MeV$ is the soft state. This may be due to synchrotron radiation. Magnetic field could be very strong in soft states due to higher Keplerian disk rate (if equipartition is assumed). If this interpretation is correct, then the power law component should not be extended in hard states till several MeV (since the magnetic field would be weaker due to equipartition with smaller disk rate).

Another important prediction of our two component model is that during the state transition, the soft component may change rather abruptly, while the hard component may change very slowly. This is because the soft component produced by the Keplerian disk which changes in a smaller time scale due to higher viscousity while the hard component will change in a smaller time scale due to the lower viscosity in the sub-Keplerian component. A factor of ten in these time scales is expected from this simple consideration alone. Indeed the recent RXTE observation of Cyg X-1 shows precisely this behavior (Zhang et al. 1997 [Z97]). Furthermore, since the transition from hard state to soft state in our model is due to the sudden increase in the Keplerian rate, (i.e., viscosity –initiated by capturing of blobs of magnetic fields for instance, which must take its advection time before viscosity goes down again and the hard state is resumed), the net luminosity may increase during the soft state even if the total rate is fixed. This is because the efficiency of emission from the sub-Keplerian component is not generally high (it depends on the number of soft photons supplied) in the hard state. This has also been seen in the recent observation of Cyg X-1 (Z97).

Fig. 5 shows examples of spectral transitions in black hole candidates in all the three models described above. We choose here $M^*_{BH} = 1M_\odot$, which after correction due to spectral hardening (Shimura & Takahara, 1995), roughly corresponds to a mass of $M_{BH} \sim 3.6M_\odot$. All the rates are in units of Eddington rate. In Fig. 5(a), we consider three disk rates $\dot{m}_d = 0.3,\ 0.05,\ 0.0005$ but the same halo rate $\dot{m}_h = 1$. Solid, long-dashed and short-dashed curves are for strong shock Model (TCAFM1), weak or no-shock Model (TCAFM2) and zero angular momentum halo Model (TCAFM3). For a set of $(\dot{m}_d, \dot{m}_h)$, the spectrum is hardest for TCAFM1 and softest for TCAFM3. This is expected since the emission region has the highest optical depth when shocks are stronger. SCAFM always produces soft states for these parameters. It can produce hard state in extreme parameter range. However, in that case during the state transition, the

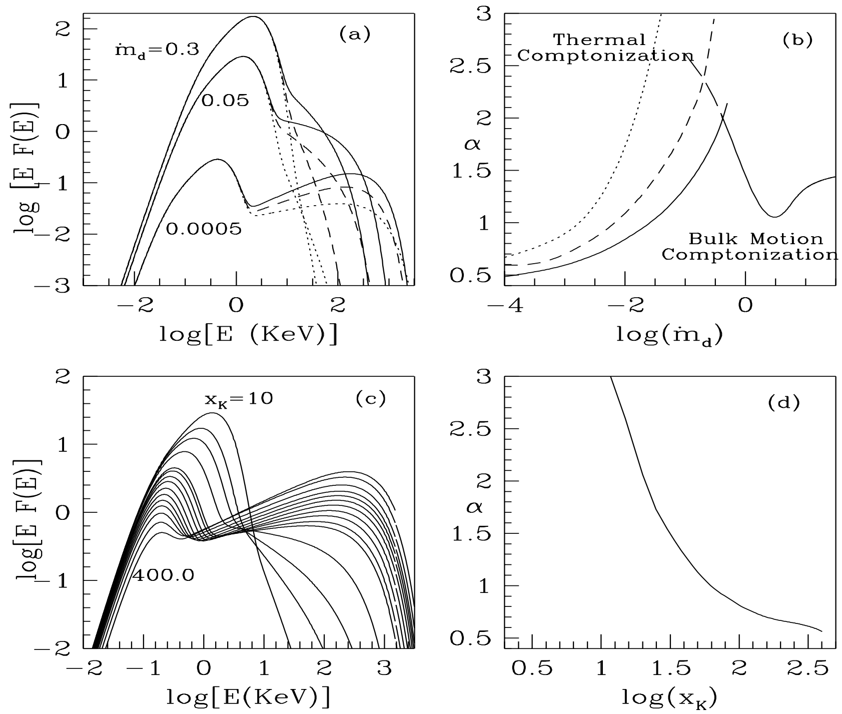

Fig. 5: Model dependence of spectral properties. (a) Solid, long-dashed and short-dashed curves are for TCAFM1, TCAFM2 and TCAFM3 respectively. (b) Spectral indices of the corresponding models as functions of $\dot{m}_d$ are drawn. (c) Result of TCAFM3 ($\dot{m}_d = 0.05$, $\dot{m}_h = 1.0$). Spectrum changes from hard state to soft state as the Keplerian disk approaches the black hole due to increase in α and $\dot{m}_d$ (as probably is the case in the rising phase of a novae outburst). (d) Changes in spectral index with x_K.

hard and soft components would always change in the same time scale which is not observed (Z97). In Fig. 5(b), we show the comparison of energy spectral index α (where $F[E] \sim E^{-\alpha}$) for these models as functions of $\dot{m}_d$. In all these models, spectra becomes soft even when the disk rate is much below Eddington rate. In the case of supermassive black holes, the behavior is very similar as the electron temperature of the sub-Keplerian region is very insensitive to the central mass ($T_e \propto M_{BH}^{0.04}$). At a high accretion rate, the bulk motion Comptonization produces weaker hard tail (CT95). Its behavior is independent of any model and depends mainly on the optical depth in the last few Schwarzschild radii outside the horizon. In the long dashed region of the convergent flow curve, both power laws due to thermal and bulk motion Comptonizations are expected in the observed spectra. In Fig. 5(c), the dependence of the spectra on the location where the flow deviates from a Keplerian disk (x_K) is shown using TCAFM3. Fig. 5(d) shows the corresponding variation of the spectral index. As described in CT95 and C96b, this variation of x_K could be simply due to the viscosity variation in the flow (see, Fig. 3 above) and therefore such variation in the spectra is expected in viscous time scale, specially during the rising phase of a novae outburst which is presumably induced by an enhancement in viscosity

(see, Cannizzo 1993 and references therein) at the outer edge of the Keplerian disk. Figs. 5(c-d) were drawn for $\dot{m}_d = 0.05$ and $\dot{m}_h = 1.0$. Indeed, rising light curves in X-ray novae derived from this consideration is remarkably similar to what is observed (C97). Just as the initial outburst of an X-ray novae could be understood by increase in the Keplerian rate (which is converted from the sub-Keplerian matter as viscosity increases; see Chakrabarti & Molteni, 1995) and consequent decrease of the inner edge of the Keplerian disk and/or the decay of the X-ray novae can also be understood from the (primarily exponential) decay of the Keplerian rate. In reality both rates must change and the relative abundances of photons and electrons will determine whether a X-ray novae will even change its state from soft to hard (as in GS1124-68 and GRS2000+25) or will remain hard for ever (as in GS2023+338, GRO J1655-40; see Grebenev et al, 1994). Decent spectral fits of GS2000+25 and GS1124-68 are presented in C97. Such transitions are best understood by numerical simulations of viscous advective flow together with radiative transfer which will be done in near future.

The quasi-periodic oscillations of black hole candidates are examples of 'puzzles' which are most naturally resolved within the framework of the TCAF model. As we have already discussed above, there seems to be two kinds of oscillations: in the case where the stable shock condition is not satisfied, but still a high entropy solution is present (inner sonic point), the flow still forms an unstable oscillating shock. The typical frequency is a function of specific angular momentum of the flow close to the inner edge (which in turn depends on viscosity, see, C96b). Generally, the time period is $4 - 6000(2GM/c^3) \sim 4 - 6(M/M_\odot) \times 10^{-2}$s (RCM97). In this case, the frequency of oscillation may be somewhat insensitive to the accretion rate of the flow, since the boundary of the region NSA of Fig. 2 depends on specific angular momentum and specific energy (which contains the information of the temperature of the disk, which in turn, depends on cooling efficiency, and hence the accretion rate). Such QPOs should be seen in sudden flare events when the specific energy temporarily becomes positive (Fig. 2) and the flow parameters are within NSA or NSW. In a second kind of QPO, the infall time scale in the post-shock flow (or, the flow crossing time scale in the centrifugally supported dense region) must be comparable to the cooling time scale (MSC96) which also becomes the timescale of periodicity. In this case, once the oscillation starts, the frequency must increase roughly proportional to the accretion rate, if the two-body processes are responsible (as in bremsstrahlung cooling). Otherwise, in hard states during thermal Comptonization, the frequency may remain vertually unchanged (since the Compton cooling time scale remains roughly constant at low disk accretion rate). As the source approaches the soft state, the Comptonization cooling behaves highly non-linearly (see, the plot of α in Fig. 5b) and hence the frequency should go up, initially linearly, but then much faster as the Keplerian rate comes closer to the Eddington rate ($\dot{m}_d \sim 0.1 - 0.3$) pretty much like the variation of α as shown in Fig. 5b.

One point to note in this context is that it is possible to find a large number of physical mechanisms which may be able to explain the *frequencies* of QPOs. However, the reason why we believe that the mechanism of oscillations as we mentioned above is operating is that it is the only way known in the literature where the oscillation amplitude could be as high as $10 - 50\%$ in normal circumstances, and possibly even higher where the actual accretion on the compact

object is impeded (MSC96). The reason is that the hard X-ray emiting region itself is dynamically 'breathing' and intercepting the variable number of soft photons, modulating the hard X-ray in the process. The soft X-ray must be modulated by very less amount (as is observed) since the variation in the inner edge of the Keplerian component by a few $(1-3)$ Schwarzschild radius does not constitute drastic change in the luminosity from the Keplerian disk. One way to check if this process is operating is to monitor the peak frequency and the luminosity of the soft X-ray bump, both of which should be anti-correlated with the luminosity of the hard X-ray. Of course, it is not necessary that the shock forms in the sub-Keplerian flow exactly where the Keplerian disk ends (Fig. 1) in which case, such correlation is difficult to predict. Other mechanisms in the literature can produce variations of only a fraction of percentage.

4. Concluding Remarks

The understanding of accretion processes on black holes has undergone a major revision in recent years when the solutions of advective disks are taken into considerations. It is now proven beyond doubt that the sub-Keplerian flow plays a major role in shaping the stationary and non-stationary spectra of black holes and neutron stars. Spectral behavior of X-ray novae and other black hole candidates (see, e.g., ETC96 for LMC X-3, Crary et al. 1996; Z97 for Cyg X-1), universal presence of the weak hard tail in very soft states of black hole candidates, diverse observations such as quiescent states to rising phases of black hole candidate novae, soft to hard transitions, pivoting property of the spectra, quasi-periodic oscillations (including observed large amplitude modulations) are naturally explained by TCAF models without invoking any additional unknown components. Though we did not include magnetic fields explicitly, existence of small fields as generated by say, Balbus-Hawley instability (Balbus & Hawley, 1994), cannot affect our results.

We already mentioned the importance of sub-Keplerian flows in the disks. It is perhaps no accident that the sub-Keplerian flows were found to be more effective in formation and collimation of cosmic radio jets observed in active galaxies (Chakrabarti & Bhaskaran, 1992). In active galaxies, the transition of states (which occur in viscous time scales) would take thousands of years! Thus, generally the spectra is also found to remain in the same 'state' for long time. Nevertheless, there are several cases where the hard component has been seen with a energy spectral slope of 1.5 (e.g., Arnaud et al. 1985). These indications, together with QPOs with periodicity of order of days (Halpern & Marshall, 1996) may actually vindicate the validity of the advective disk model around both galactic and extra-galactic black hole candidates.

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